

## Satellite observations of cloud plumes generated by Nauru

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**Abstract.** A cloud plume is generated by the interaction of low-level easterly flow and diurnal surface heating on the island of Nauru in the tropical Pacific. Diurnal and seasonal cycles of cloud plume length, frequency, and heading were obtained by inspection of a year of hourly daytime GMS images. The cloud plume extends downwind and typically grows during the day to a mean length of 125 km by late afternoon with a maximum observed length of 425 km. The longest average plumes occur during March and April. The afternoon plume frequency was 63% compared to 50% for all observations. Further evaluation of the plume effects is needed to fully assess their impact on the development of long-term statistics of cloud and radiation parameters derived from surface instruments on the island's leeward side.

### Introduction

Developing comprehensive climatological observations of the marine atmosphere is difficult because of the lack of a stable platform with sufficient power and environmental protection. Using small islands for such observations is virtually the only alternative, but island orography can disturb the low-level flow and alter the cloud cover over and downwind of the island [e.g., Minnis *et al.* 1992]. To minimize such effects, it is desirable to select a location that is relatively flat. As part of the Atmospheric Radiation Measurement (ARM) program, the second Atmospheric Radiation and Cloud Station (ARCS-2) was placed on the leeward side of Nauru (0.52°S, 166.92°E), an island with a maximum elevation of 65 m, to monitor the equatorial Tropical Western Pacific (TWP). Nauru is located in the subsidence zone between the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). Measurements of meteorological state, radiation, and cloud properties from Nauru are hopefully representative of the surrounding ocean. Observations at ARCS-2 started during the Nauru99 field campaign (mid-June to mid-July 1999).

During Nauru99, island-induced clouds in the form of plumes were observed overhead at the ARCS-2 site. Although the plumes are probably an insignificant part of the overall radiation budget in the TWP, they are observed by the ARCS-2 measurement system and may bias the observations relative to the surrounding ocean. Given the goals of ARM, it is critical to know how these cloud plumes affect the measurements taken at ARCS-2 and whether the ARCS-2 data are sufficiently representative of the surrounding ocean. To help address these questions, this paper documents the spatial and temporal

variations of the Nauru cloud plumes determined from high-resolution satellite imagery.

### Cloud Plume Data and Methods

Hourly visible (VIS, 0.65μm) Geostationary Meteorological Satellite (GMS-5) 1.25-km images from June 15, 1999 to June 30, 2000 were examined for cloud plumes between 0730-1630 local standard time (LST). Figure 1 shows an example of cloud plume evolution in GMS images taken October 28, 1999. At the beginning of the day (0730 LST), no plume is present. One hour later, the plume has formed and increases until the last visible image at 1630 LST when the cloud plume reaches an extent of ~200 km. Cloud plumes cannot be identified in the GMS infrared (IR, 10.8 μm) imagery because of decreased resolution and the small temperature difference between plume and ocean. In Figure 1g, the older part of the plume changes direction to the southwest, apparently a result of rising to the level of the background low-level clouds.

The images were examined manually for three conditions. First, clouds obscure the island (usually optically thick convective clouds); second, a plume is detected; and third, no plume is observed. If a cloud plume is observed, its length and direction are calculated by measuring the distance between the island and the endpoint and noting its direction from Nauru. The estimation of length is somewhat subjective because the plume sometimes blends in with background low cloud formations that tend to have similar features. However, because the plume is usually brighter than the background clouds, a suspected plume-cloud was not counted as part of the plume in these cases unless it was brighter than the surrounding clouds and was consistent with the plume motion in image sequences. Sometimes, the plume appears segmented.

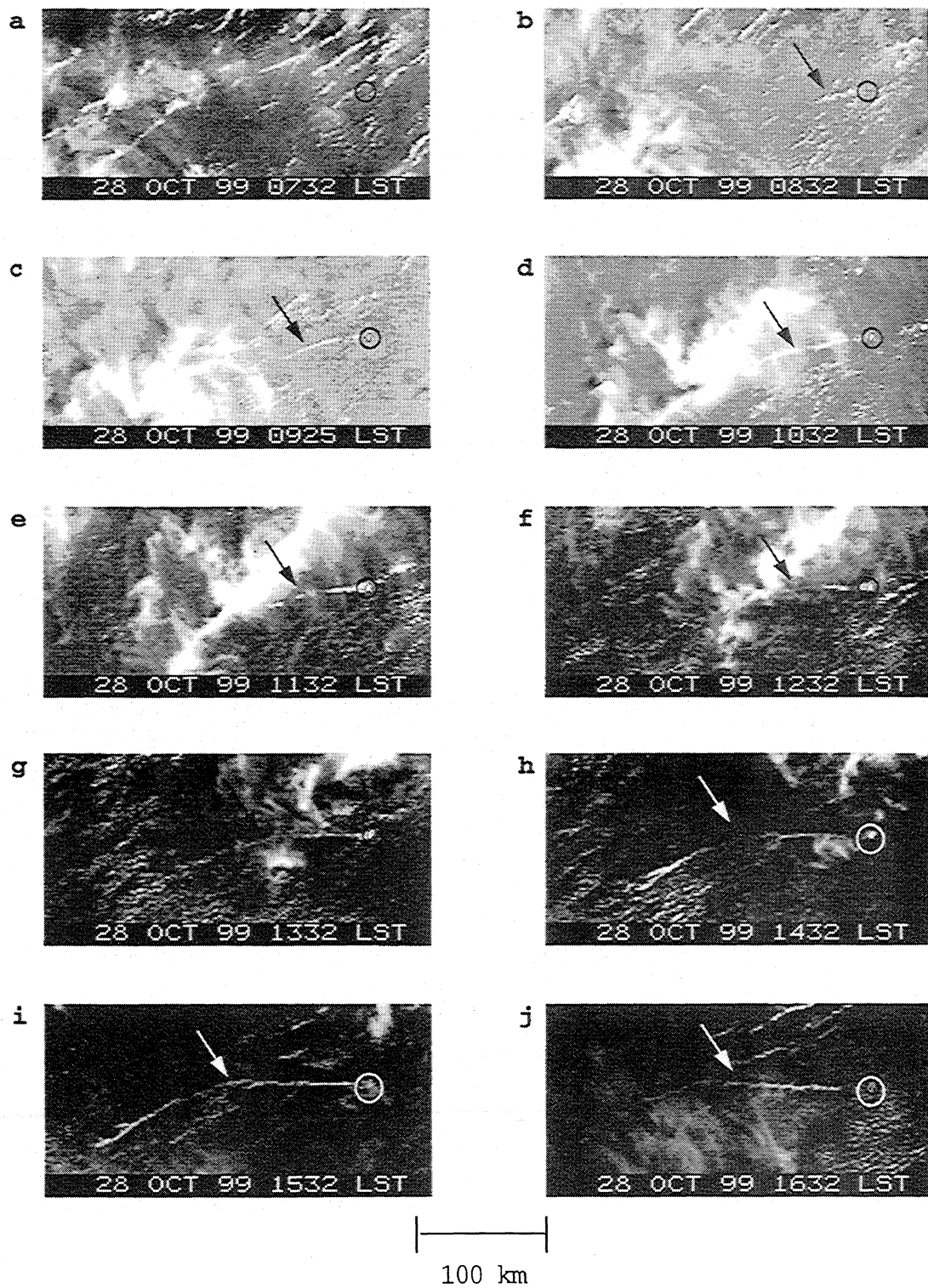
### Cloud Plume Length

While orographic lifting and island generated aerosols may be contributors, the plume formation appears primarily to be the result of the diurnal heating of the island and subsequent convection of moist low-level air advected almost continuously over the island by the prevailing easterly trade winds. For the days with a complete record of VIS images, unobscured plumes were observed 53% of the time. During 92% of these days, the plume was first observed between 0800 and 1300 LST. During Nauru99, the diurnal range in surface air temperature was 3°C at ARCS-2, while the skin temperature diurnal range, as deduced from pyrometer data, averaged 9.6°C. Surface air temperatures from soundings launched by the Nauru99 ships and the ARCS-2 show that the island and ocean air temperatures are equal at midnight, but the island air temperature is ~4.5°C greater than that of the surrounding ocean by 1030 LST. Thus, the island is a significant heat source during the daytime. Figure 2 shows the mean plume

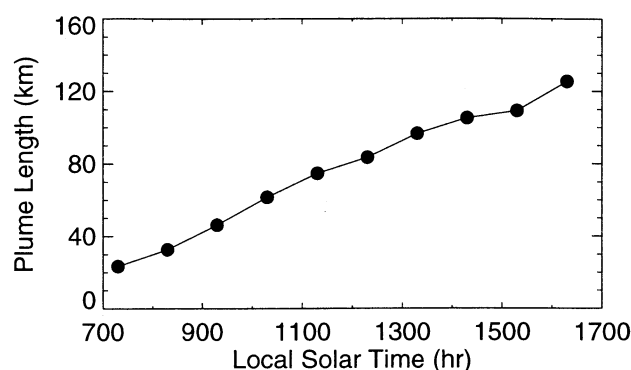
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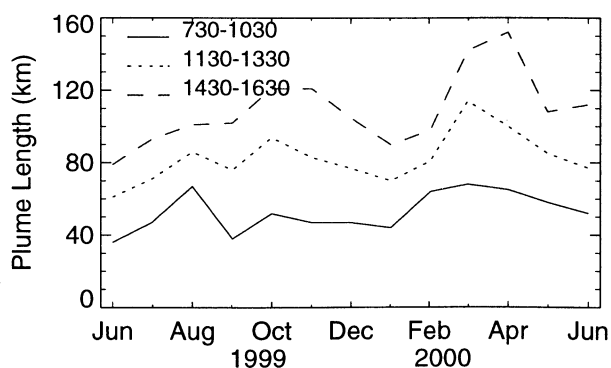
**Figure 1.** GMS 1.25-km imagery showing cloud plume evolution from Nauru (in the circle) during 27-28 October 1999. Arrows indicate the location of the cloud plume.



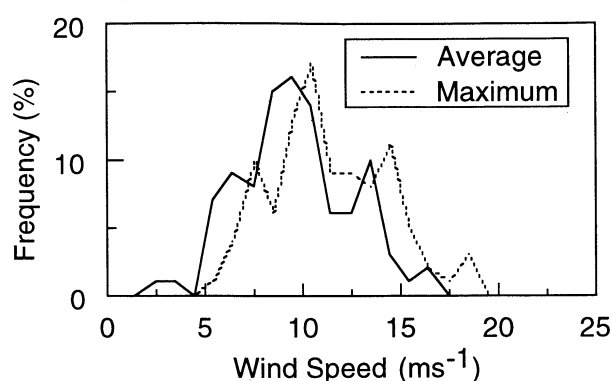
**Figure 2.** Hourly mean length of cloud plumes from June 1999 to June 2000 (solid line). Dotted line indicates the one-standard deviation values.

length at each local hour for any time when a plume was observed. For the study period, the average plume length increases almost linearly throughout the day. The average cloud plume length at 1630 LST is  $125 \pm 75$  km, while 95% of all plumes were shorter than 200 km. The clouds that developed during the day may continue advecting downwind overnight. In 3% of the cases, the plume may have formed before sunrise or may not have entirely dissipated. For example, a 46-km plume was detected at 0730 LST, Nov. 18, 1999 and was detectable in the sunrise image at 0630 LST. Without high-resolution multispectral imagery, it is not possible to determine the cloud plume presence at night.

Figure 3, showing the monthly mean plume lengths, reveals that plume length peaks during the fall and spring. The longest plume occurred during April 21, 2000 reaching a length of 425 km at 1630 LST. The image sequence indicated a growth rate ranging from 45 - 76 km/hr, while the balloon sounding (1030 LST) for the day yields a wind speed of 54 km/hr at 920 hPa. Thus, the plume's growth rate is consistent with advection. Figure 2 suggests that the mean growth rate for the study period is 10.2 km/hr. Examination of the plume length from plume start time using the unobscured days yields an 11 km/hr growth rate. However, the average plume length when a plume is first observed is 46.6 km. Histograms of mean and maximum wind speeds between 950 and 850 hPa are shown in Figure 4 for data from rawinsondes launched at 1030 LST between June 1999 and May 2000 when plumes were observed. The average maximum and mean wind speeds of 42



**Figure 3.** Monthly mean length of cloud plumes from June 1999 to June 2000 for different daytime segments.



**Figure 4.** Frequency of wind speed between 950-850 hPa from 1030 LST (2330 UTC) rawinsonde data when plumes were present.

km/hr and 35 km/hr, respectively, are considerably larger than the estimated mean growth rate but very consistent with the growth rate during the first hour. Thus, the plume growth is not entirely an advective process; it is more likely a balance between advective, entrainment, and precipitation processes. Further examination of these influences is beyond the scope of this paper.

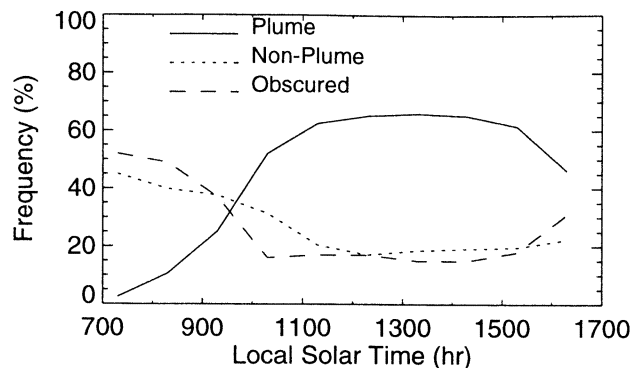
### Cloud Plume Heading

The mean directional heading (from north) of the cloud plumes was  $265^\circ$  (plume forming to the west of the island) with no significant diurnal cycle. From June 1999 to June 2000, the mean heading gradually shifted from  $270^\circ$  to  $260^\circ$ , except for Sept. 1999 when the average orientation was  $280^\circ$ . Individual headings ranged from  $220^\circ$  to  $320^\circ$  with a standard deviation of  $20^\circ$ . Plumes were typically shorter than average when their headings were not between  $240^\circ$  and  $300^\circ$ . An anomaly occurred Jan. 22, 2000 when the heading was  $130^\circ$ .

From the coincident rawinsonde data, the wind direction at plume top was assumed to correspond to the maximum wind speed between 850 and 950 hPa. The mean difference between the plume heading and wind direction plus  $180^\circ$  is less than  $2^\circ$ . The rms difference is  $13^\circ$ , which is within one standard deviation of the plume direction. In the GMS IR images taken during the study period, the ITCZ was observed between  $5^\circ$  and  $10^\circ$ N and the SPCZ from  $5^\circ$  to  $10^\circ$ S confirming that no large-scale circulation changes and little seasonal variation in directional heading had occurred. Generally, the vertical cloud structure may be characterized in the following manner: the plume heading west at the lowest atmospheric level, followed by the low-level clouds heading southwest, and the high-level cirrus heading towards the northeast.

### Cloud Plume Frequency

Figure 5 shows the frequency of plume, non-plume and obscured conditions during the period of study. The three categories are constant after 1130 LST except near sunset. The mean plume frequency is  $\sim 50\%$  for all observations and  $63\%$  during the afternoon. Obscured conditions, which are usually due to deep convective clouds, are mostly observed in the morning when the non-plume probability is greatest. Grouping the data into two periods, morning (0730-0930 LST)

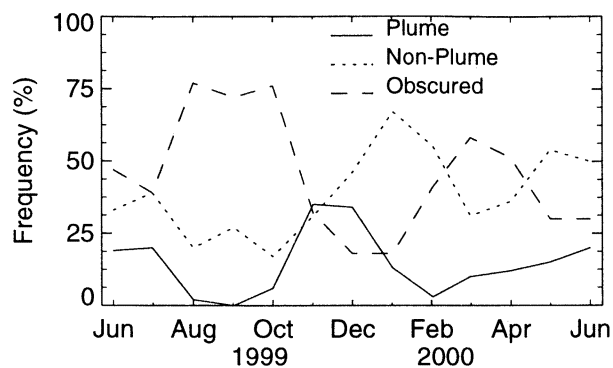


**Figure 5.** Hourly mean occurrence of cloud plume, non-plume and obscured conditions.

and the rest of the day, revealed that most of the seasonal variability occurred in the morning. In fact, no significant seasonal cycle was found between 1030 and 1630 LST. Figure 6 shows the morning category frequencies. Obscured or convective conditions peaked during September and March, whereas plume frequency peaked in November and December. The morning frequency variations are likely the result of seasonal changes in atmospheric stability. Perhaps, the Nauru surface observations could be used to determine the frequency of plume occurrence in obscured conditions to clarify the source of the seasonal minimum.

## Conclusions and Future Work

The ARM site is located on the leeward side of the island of Nauru. If the frequency of plume occurrence is indicative of plumes observed at ARCS-2, then the prevalence of afternoon plumes would increase the low cloud amount at ARCS-2 and skew the statistics relative to the surrounding ocean. Plume generation is not unique to Nauru; plumes were also observed in the GMS imagery extending from the island of Banaba ( $0.8^{\circ}\text{S}$ ,  $169.5^{\circ}\text{E}$ ) and are likely to be found over other tropical islands. However, the island effects are probably not, in general, a dominant forcing function in the tropical marine boundary layer. The plumes are similar to the low clouds that are already present, but slightly lower in altitude. Some cloud monitoring instruments, such as radar, should be able to monitor the high clouds through the plume. It may be preferable to move ARCS-2 to a windward site to minimize the island effects, although it has not been determined how much better the windward side represents the surrounding ocean.



**Figure 6.** Monthly mean occurrence of cloud plume, non-plume and obscured conditions between 0730 and 0930 LST.

This paper provides the most detailed analysis to date of an island-induced cloud plume, however, much additional research is needed to fully determine the effects on the ARM measurements. GMS-derived cloud amounts and radiation for a small region centered on the ARCS-2 site should be compared with ARCS-2 data to determine whether the plumes have any significant radiative impact. Multispectral imagery should also be used to infer the plume microphysical properties to determine if they differ substantially from the low clouds generated over the water. Comparison between GMS-derived parameters and the instrument measurements obtained from the research ships, *Mirai* and *Ron Brown*, during Nauru99 will help determine the robustness of the GMS retrievals. Comparisons between the ARCS-2 and ship data as well as GMS retrieval over and away from the island will help quantify any biases resulting from this persistent phenomenon.

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